
Steven T. Taylor

The Fundamentals of Expansion Tanks

BY STEVEN T. TAYLOR, P.E., FELLOW ASHRAE

Who would have thought such a simple piece of equipment, the expansion tank, could be so misunderstood, including significant errors and misunderstandings in published standards, handbooks, and manufacturer's installation manuals? In this month's column, I hope to clear up some of these issues and to provide simple advice for expansion tank sizing and piping.

I first got into the details of how expansion tanks work when working as a commissioning agent for a mid-rise office project in the late 1990s. The building operator claimed the mechanical engineer made design errors because:

- The pressure at the bottom of the heating system would rise to about 100 psig (690 kPag) when it warmed up each morning, higher than the operator was used to seeing.
- The expansion tank, which was a precharged bladder type tank, was not located at the pump suction, as per the manufacturer's installation and operating manual (IOM), which stated, "…the expansion tank must be connected as close as possible to the suction side of the system circulating pump for proper system operation." Instead, the tank was located on the roof, while the pumps (and boilers) were in the basement.
- The tank size was too small according to the sizing equation in the mechanical code.

In fact, after looking into the details and fundamentals of expansion tanks, which ultimately resulted in an *ASHRAE Journal* article, "Understanding Expansion Tanks," published in 2003,[1] I concluded there was nothing at all wrong with the installation:

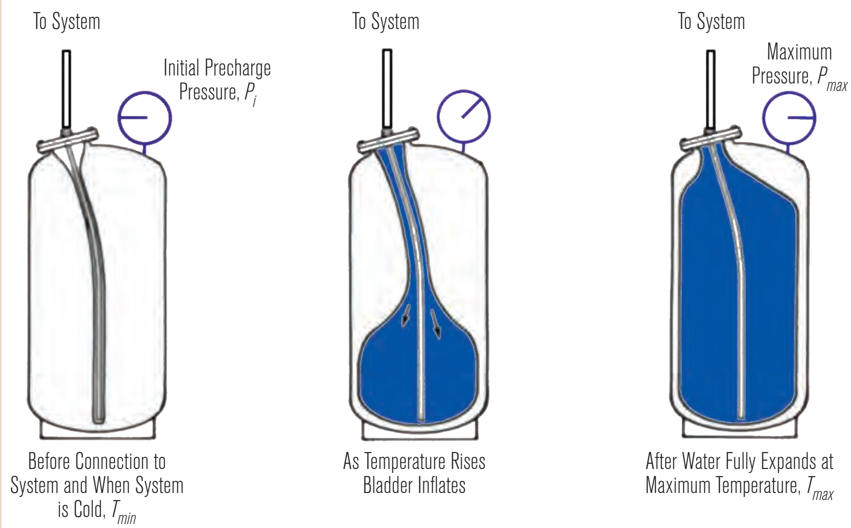
- The pressure was well below the boiler and piping system component limits—all were rated for over 150 psig at 200°F (1034 kPag at 93°C)—so while the pressure was higher than the operator was used to, it was not excessive.
- The manufacturer's IOM was simply wrong. The tank can literally be located anywhere in the system, provided its precharge pressure and size are properly selected. In this case, locating the tank on the roof resulted in the smallest and least expensive tank.
- The sizing equation in the model mechanical codes, both the Uniform Mechanical Code[2] and International Mechanical Code,[3] do not apply to precharged expan-

Steven T. Taylor, P.E., is a principal of Taylor Engineering in Alameda, Calif. He is a member of SSPC 90.1.

sion tanks; they were extracted from the *ASME Boiler and Pressure Vessel Code-2015*, Section VI,[4] and developed many years ago for plain steel expansion tanks. They result in larger than necessary sizes for precharged expansion tanks.*

To understand these issues, we need to revisit the fundamentals. Some of this discussion is extracted from the "Understanding Expansion Tanks" article referenced above, but I have not repeated all the details of how to determine expansion tank design pressures. Instead, these calculations have been incorporated into a relatively easy to use spreadsheet, described below. In addition, information has been added showing how expansion tank sizing formulas were derived (see sidebar, "Expansion Tank Sizing Formulas"), and typical expansion tank piping requirements are described in detail (see sidebar, "Typical Expansion Tank Piping").

FIGURE 1 Bladder expansion tank.



Purpose

Expansion tanks are provided in closed hydronic systems to:

- Accept changes in system water volume as water density changes with temperature to keep system pressures below equipment and piping system component pressure rating limits.
- Maintain a positive gauge pressure in all parts of the system to prevent air from leaking into the system.
- Maintain sufficient pressures in all parts of the system to prevent boiling, including cavitation at control valves and similar constrictions.
- Maintain net positive suction head required (NPSHR) at the suction of pumps.

The latter two points generally apply only to high temperature (greater than approximately 210°F [99°C]) hot water systems. For most HVAC applications, only the first two points need to be considered.

Tank Styles

There are four basic styles of expansion tanks:

1. Vented or open steel tanks. Since they are vented, open tanks must be located at the highest point of the system. Water temperature cannot be above 212°F (100°C), and the open air/water contact results in a constant migration of air into the system, causing corrosion. Accordingly, this design is almost never used anymore.

2. Closed steel tanks, also called plain steel tanks or compression tanks by some manufacturers. This is the same tank style as the vented tank, but with the vent capped. This allows the tank to be located anywhere in the system and work with higher temperatures. But they still have the air/water contact that allows for corrosion, and sometimes a gradual loss of air from the tank as it is absorbed into the water.

Unless precharged to the minimum operating pressure prior to connection to the system, this style of tank also must be larger than precharged tanks. (See sidebar, "Expansion Tank Sizing Formulas.") Accordingly, this design is also almost never used anymore.

3. Diaphragm tanks. This was the first design of a compression tank that included an air/water barrier (a

* These codes include a table that includes a column for "pressurized diaphragm type" tanks, correctly sized but limited to systems with 195°F (91°C) average operating temperature, 12 psig (83 kPag) precharge pressure and 30 psig (200 kPag) maximum pressure. No tables or equations are provided for other applications.

Expansion Tank Sizing Formulas

One of the first, and still the foremost, major publications on expansion tank sizing was written by Lockhart and Carlson[6] in 1953. The authors derived the general formula for tank sizing, *Equation 1* (with variable names adjusted to match those used in this article), from basic principles assuming perfect gas laws:

$$V_t = \frac{V_s\left(E_w - E_p\right)}{\dfrac{P_sT_c}{P_iT_s} - \dfrac{P_sT_h}{P_{max}T_s} - E_{wt}\left[1 - \dfrac{P_sT_c}{P_{max}T_s}\right] + E_t} - 0.02V_s \qquad (1)$$

Where

V_t = tank total volume

V_s = system volume

P_s = starting pressure when water first starts to enter the tank, absolute

P_i = initial (precharge) pressure, absolute

P_{max} = maximum pressure, absolute

E_w = unit expansion ratio of the water in the system due to temperature rise

= $\left(\frac{v_h}{v_c} - 1\right)$

v_h = the specific volume of water at the maximum temperature, T_h.

v_c = the specific volume of water at the minimum temperature, T_c.

E_p = unit expansion ratio of the piping and other system components in the system due to temperature rise

= $3\alpha\left(T_h - T_c\right)$

α = coefficient of expansion of piping and other system components, per degree

T_h = maximum average water temperature in the system, degrees absolute

T_c = minimum average water temperature in the system, degrees absolute

T_s = starting air temperature in the tank prior to fill, degrees absolute

E_{wt} = unit expansion ratio of water in the tank due to temperature rise

E_t = unit expansion ratio of the expansion tank due to temperature rise

The last term ($0.02\,V_s$) accounts for additional air from desorption from dissolved air in the water.

This equation can be simplified to *Equation 2* by ignoring small terms and assuming tank temperature stays close to the initial fill temperature (typically a good assumption, assuming no insulation on the tank or piping to it, which is a common, and recommended, practice):

$$V_t = \frac{V_s\left[\left(\dfrac{v_h}{v_c} - 1\right) - 3\alpha\left(T_h - T_c\right)\right]}{\dfrac{P_s}{P_i} - \dfrac{P_s}{P_{max}}} \qquad (2)$$

This equation includes the credit for the expansion of the piping system. This term is also relatively small and the expansion coefficients are hard to determine given the various materials in the system, but it is included in *Equation 2* since it is included in the *ASHRAE Handbook*[7] sizing equations, which in turn were extracted from an article by Coad.[8] This term is also included in some, but not most, expansion tank manufacturers' selection software. Most manufacturers conservatively ignore this term since it is small and no larger than the terms already ignored in *Equation 2*. Ignoring this term results in *Equation 3*.

$$V_t = \frac{\left(\dfrac{v_h}{v_c} - 1\right)V_s}{\dfrac{P_s}{P_i} - \dfrac{P_s}{P_{max}}} \qquad (3)$$

The numerator is the volume of the expanded water, V_e, as it warms from minimum to maximum temperatures, so the equation can be written:

$$V_t = \frac{V_e}{\dfrac{P_s}{P_i} - \dfrac{P_s}{P_{max}}} \qquad (4)$$

flexible membrane, to eliminate air migration) and that was designed to be precharged (to reduce tank size). The flexible diaphragm typically is attached to the side of the tank near the middle and is not field replaceable; if the diaphragm ruptures, the tank must be replaced.

4. Bladder tanks. Bladder tanks use a balloon-like bladder to accept the expanded water. Bladders are often sized for the entire tank volume, called a "full acceptance" bladder, to avoid damage to the bladder in case they become waterlogged. Bladders are gener-

Where

V_e = $(v_h/v_c-1)V_s$

Equation 4 can be further simplified based on the style of tank used. For vented tanks, the pressures are all the same and the dominator limits to 1, so the tank size is simply the volume of expanded water:†

Vented Tank
$$V_t = V_e \quad (5)$$

For unvented plain steel tanks, the starting pressure is typically atmospheric pressure with the tank empty (no precharge). The tank is then connected to the makeup water, which pressurizes the tank to the fill pressure by displacing air in the system, essentially wasting part of the tank volume. So the sizing equation‡ is:

Closed Tank (no precharge)
$$V_t = \frac{V_e}{\frac{P_a}{P_i} - \frac{P_a}{P_{max}}} \quad (6)$$

Where

P_a = atmospheric pressure

For any tank that is precharged to the required initial pressure, including properly charged diaphragm and bladder tanks, but also including closed plain steel tanks if precharged, P_s is equal to P_i so the sizing equation reduces to:

Precharged Tank
$$V_t = \frac{V_e}{1 - \frac{P_i}{P_{max}}} \quad (7)$$

Note that this equation only applies when the tank is precharged to the required P_i. Tanks are factory charged to a standard precharge of 12 psig (83 kPag).§ For higher desired precharge pressures, either a special order can be made from the factory or the contractor must increase the pressure with compressed air or a hand pump. But it is not uncommon for this to be overlooked. This oversight can be compensated for by sizing the tank using *Equation 8* (assuming atmospheric pressure at sea level):

Closed Tank
(12 psig/26.7 psia [83 kPag/184 kPaa] precharge)

$$V_t = \frac{V_e}{\frac{26.7}{P_i} - \frac{26.7}{P_{max}}} \quad (8)$$

This will increase the tank size vs. a properly precharged tank.

ASME Boiler and Pressure Vessel Code-2015, Section VI, includes sizing equations (as do the UMC and IMC, which extract the equations verbatim), as shown in *Equation 10*, with variables revised to match those used in this article:

$$V_t = \frac{V_s\left(0.00041T_h - 0.0466\right)}{\frac{P_a}{P_i} - \frac{P_a}{P_{max}}} \quad (9)$$

Comparing the denominator of *Equation 9* to *Equation 6*, this formula is clearly for sizing a non-precharged tank; it will overestimate the size of a precharged tank.

The numerator is a curve fit of V_e; it assumes a minimum temperature of 65°F (18°C) and is only accurate in the range of about 170°F to 230°F (77°C to 110°C) average operating temperature. Therefore, this equation cannot be used for very high temperature hot water (e.g. 350°F [177°C]), closed-circuit condenser water, or chilled water systems.

† In the *2016 ASHRAE Handbook—Systems and Equipment,* Chapter 13, the analogous equation includes a factor of 2, doubling tank size. This is a common, but unnecessarily conservative, safety factor to ensure the tank does not overflow.

‡ In the *2016 ASHRAE Handbook Systems and Equipment,* Chapter 13, the analogous equation is said to apply to all closed plain steel tanks. In fact, it only applies to any tank that is not precharged.

§ The 12 psig (83 kPag) standard precharge comes from old residential construction where the boiler and expansion tank are typically in the basement. This results in a slight positive pressure at the top of the system in a typical two-story house.

ally field replaceable. This is now the most common type of large commercial expansion tank. (See sidebar, "Typical Expansion Tank Piping," for a typical piping diagram.)

The three closed type expansion tanks described above work by allowing water to compress a chamber of air as the water expands with increasing temperature (*Figure 1*). When the system is cold and the water in the tank is at minimum level (which may be no water at all), the tank pressure is at its initial

Typical Expansion Tank Piping

Figure 2 shows how bladder expansion tanks are typically piped. Notes corresponding to numbers in the figure are as follows:

1. Vertical tanks are most common for commercial projects and mounted on the floor for ease of construction and maintenance access. Horizontal tanks are also available for suspension from the structure above where floor space is inadequate.

2. If makeup water is located at the expansion tank as shown, the pressure reducing valve (PRV) setpoint may conveniently be the same as the precharge pressure of the tank (P_i) so the two are coordinated regardless of pump operation. It is possible, and sometimes necessary, to have the two separated. For instance, there may not be a convenient makeup water source near the preferred tank location (see Note 5, for example).

In this case, the PRV setpoint must be adjusted to account for the elevation difference between the PRV and tank. In this case, however, the pressure at the PRV will vary depending on pump operation. To avoid overfilling the system, the makeup water connection must be valved off once the system is filled and air removed (see Note 3). In addition, because some overfilling will inevitably occur, the tank should be sized conservatively.

3. Once the system is filled and air is removed, the makeup water connection should be valved off. This prevents "feeding a flood" should there be a major leak in the system.[#] When the system has small normal water losses, e.g., at automatic air vents and pump seals, the valve will have to be reopened occasionally. A low-pressure alarm (Note 7) can be used to indicate when a refill is needed.

4. A bypass around the PRV is recommended to reduce the time required to fill the system. Higher fill velocities also tend to help the water entrain air bubbles and carry them toward the manual air vents at high points.

5. Makeup water must be protected with backflow preventers, per code. The available pressure must be above the PRV setpoint. For high-rise buildings with multiple domestic (or reclaimed) water pressure zones and where the tank is located low in the building, it is usually necessary to connect to the high pressure zone riser rather than the low pressure zone serving plumbing fixtures at the tank location. This requirement is commonly overlooked.

6. A pressure relief valve must be located between the tank isolation valve (Note 11) and the system connection, so it is available even when the tank is valved off for maintenance. On hot water systems, this valve will be located at the boiler (per code), so it cannot be valved off from the heat source.

7. A gauge pressure sensor or switch connected to the building automation system is recommended to generate an alarm when the pressure drops below the minimum pressure (P_i), indicating either the system needs refilling (see Note 3) or a major leak has occurred.

8. Expansion tank installation and operating manuals (IOMs) generally recommend connecting to the side of the system main piping, rather than the bottom (where debris might migrate to the tank) or top (where air may result in an air lock). If a bottom connection cannot be avoided, a dirt leg with drain should be installed.

9. Sizing of the piping from the tank to the system is somewhat controversial. In normal operation, the flow rate of water as it moves back and forth to and from the tank is very low. Even after a cold start, the water temperature and volume in the system generally rise slowly so the flow rate, and resulting pressure drop, are low. A 0.75 in. (19 mm) line should be more than

[#] On one of our early high-rise projects in the late '80s, an improperly supported pipe caused a pump casing to crack, causing a major leak. Naturally, the break occurred over a weekend when no one was around. The pump was located on the 30th floor. A security guard in the lobby noticed the leak when water poured onto his desk after leaking through all 29 stories of office space. The damage would have been minimal if the makeup water valve had been closed.

or precharge pressure, P_i. As the water in the system expands upon a rise in temperature, water flows into the tank and the air pocket is compressed, increasing both the air and water system pressure. When the system is at its highest temperature and the tank water volume is at its design capacity, the resulting air and water system pressure will be equal to or less than the design maximum pressure, P_{max}. Both P_i and P_{max} are predetermined by the designer as part of the tank selection process.

adequate in this case, regardless of system size. (A larger line may be desired for makeup water on very large systems just to reduce fill time, but it is not needed for the expansion tank.) However, at least two large manufacturers of expansion tanks include in their IOMs a pipe sizing table that varies pipe size as a function of boiler capacity, length of piping, and design water temperature, with pipe sizes as large as 2.5 in. (64 mm). The table has apparently been around for years and the assumptions used to determine the pipe sizes are apparently no longer known to the manufacturers, based on enquiries to the factory. In the author's opinion, it would take an almost explosive rate of temperature change to make the flow rate and pressure drop through a 0.75 in. (19 mm) pipe cause the relief valve to open; and if that happens, so be it—that is what the relief valve is for.

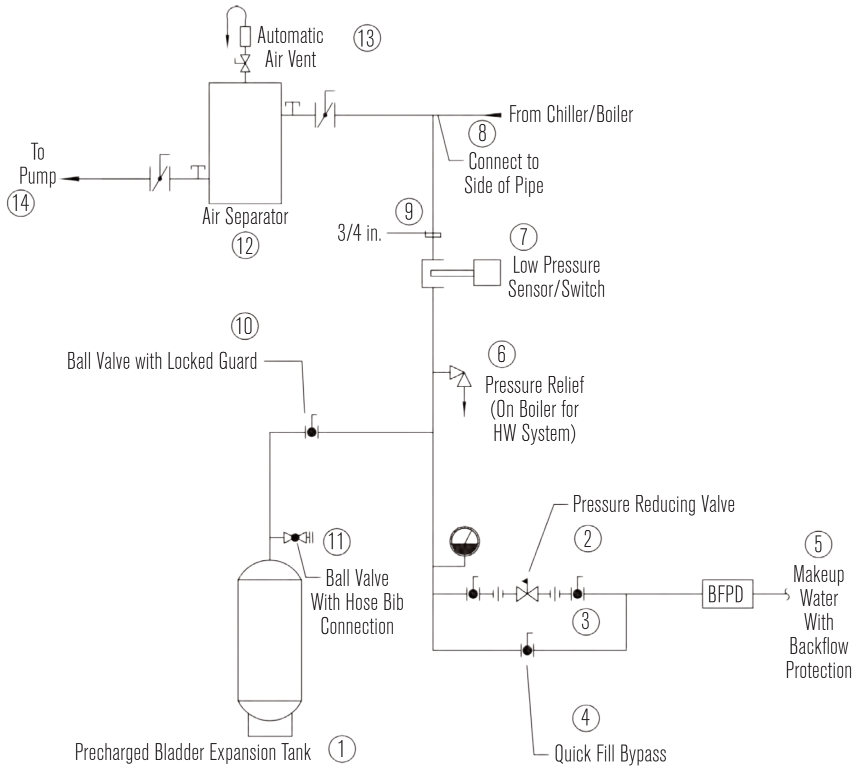


FIGURE 2 Typical expansion tank piping.

10. An isolation valve is needed to isolate the tank for service. To prevent accidental discharge of the relief valve due to overpressure, a lock guard or shield should be installed, or the valve handle can simply be removed, to discourage inadvertent closing of the valve.

11. A drain valve is needed at the tank to empty it for service and to check and recharge air pressure.

12. An air separator is not actually part of the expansion system (and not required on all systems), but is shown here so its relationship with the tank connection is clear. Locating it downstream of the makeup water supply allows some of the air dissolved in the makeup water to be immediately removed. Some manufacturers' IOMs show the makeup water upstream of the air separator and the tank connection downstream to keep the tank connection close to the pump suction. But this compromises the advantage of keeping the makeup and tank together (Note 2), and there is usually no benefit to having the tank connection right at the pump inlet (Note 14). However, either design will work satisfactorily.

13. An automatic air vent should be installed even if the air separator is not used. Some tank manufacturers' IOMs show automatic air vents right at the expansion tank, but this should not be needed when the tank is located below the piping main; air will rise up to the vent in the main.

14. The figure shows the expansion tank upstream of the pump. As explained in "Understanding Expansion Tanks," this is often the best location from a cost perspective, but not always. In fact, the tank can be located anywhere in the system as long as P_i and P_{max} are properly determined.

The referenced article "Understanding Expansion Tanks" goes into great detail about how to determine the precharge and maximum pressures as well as pressure relief valve setpoints. To improve ease of use and accuracy, this procedure has been automated in an expansion tank selection calculator spreadsheet[5] that may be downloaded for free from the author's website. Automated features include:

- Calculation of water volume in piping based on pipe size and length;

- Determination of the critical pressure point based on equipment ratings and elevations;
- Calculation of pressure relief valve setpoint;
- Determination of vapor pressure values based on fluid temperature;
- Suggested high and low temperature values based on application; and
- Calculation of expanded water volume and total tank size.

All that is required to make the final expansion tank selection is the manufacturer's catalog or submittal data.

Conclusions

Expansion tanks are a necessary part of all closed hydronic systems to control both minimum and maximum pressure throughout the system. They are simple pieces of equipment, but many misunderstandings exist in manufacturer's manuals, codes, and engineering guides about where expansion tanks can and should be located, how they are sized, and how they are piped. This column, along with my prior article, "Understanding Expansion Tanks," should provide all the information needed to properly design hydronic thermal expansion systems.

References

1. Taylor, S. 2003. "Understanding expansion tanks." *ASHRAE Journal* (March).

2. *Uniform Mechanical Code-2015.*

3. *International Mechanical Code-2015.*

4. *ASME Boiler and Pressure Vessel Code-2015,* Section VI, Recommended Rules for the Care and Operation of Heating Boilers.

5. Taylor Engineering. 2016. "TE Expansion Tank Selection Calculator, v1.6." http://tinyurl.com/j9l8ydk.

6. Lockhart, H., G. Carlson. 1953. "Compression tank selection for hot water heating systems." *ASHVE Transactions* 59:55–76.

7. *2016 ASHRAE Handbook—Systems and Equipment*, Chap. 13, Equations 13 to 15.

8. Coad, W. 1980. "Expansion tanks," *HPAC Engineering* (May). ■